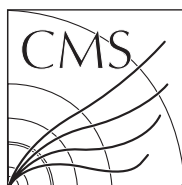


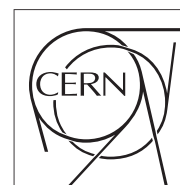
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The Compact Muon Solenoid Experiment

Conference Report

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Calorimetry at the LHC

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Abstract

The Large Hadron Collider (LHC) is the new CERN accelerator that will provide proton proton collisions at $\sqrt{s} = 14$ TeV. It will have two general purpose experiments: ATLAS and CMS, and two dedicated experiments: Alice, to study heavy ion collisions, and LHCb, to study b physics. The LHC is an explorative machine built to search for the Higgs boson and physics beyond the Standard Model. Calorimeters play a crucial role in these searches. In particular the electromagnetic calorimeter is fundamental in the search for the SM Higgs boson, depending on the mass range, either in the two photon decay channel or in the four leptons channel. Hadron calorimeters are important for super-symmetric particles searches where jets and missing transverse energy are expected. We present a review of the LHC experiments calorimeters and their expected performance.

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Calorimetry at the LHC

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The Large Hadron Collider (LHC) is the new CERN accelerator that will provide proton proton collisions at $\sqrt{s} = 14$ TeV. It will have two general purpose experiments: ATLAS and CMS, and two dedicated experiments: Alice, to study heavy ion collisions, and LHCb, to study b physics. The LHC is an explorative machine built to search for the Higgs boson and physics beyond the Standard Model. Calorimeters play a crucial role in these searches. In particular the electromagnetic calorimeter is fundamental in the search for the SM Higgs boson, depending on the mass range, either in the two photon decay channel or in the four leptons channel. Hadron calorimeters are important for super-symmetric particles searches where jets and missing transverse energy are expected. We present a review of the LHC experiments calorimeters and their expected performance.

Keywords: Calorimetry, high energy physics

1. The Large Hadron Collider

The Large Hadron Collider is the new CERN hadron collider that will provide proton-proton collisions at $\sqrt{s} = 14$ TeV. The design luminosity is $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and the bunch crossing spacing is 25 ns. Two general purpose experiments will take data at the LHC: ATLAS and CMS, and two dedicated experiments will perform specific studies: b physics (LHCb) and heavy ion collisions (Alice).

The physics program of ATLAS and CMS is to search for the Higgs boson and to study the physics beyond the Standard Model. In addition many standard particles, like top and beauty quarks, can be studied with high statistics.

The LHC will explore the existence of the Higgs boson from the present LEP limit¹ of 114.4 GeV. Depending on the H mass, the analysis uses the $H \rightarrow \gamma\gamma$ decay or $H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons respectively in the low and high

mass range. These channels have electrons or photons in the final state and require a very good energy and position resolution. The electromagnetic calorimeters of ATLAS and CMS have been optimized on the $H \rightarrow \gamma\gamma$ channel which is the most demanding.

In events with super-symmetric particles production typically leptons, jets and neutralinos are present in the final state. So good energy and position resolution also for jets and missing energy is required. The hadronic calorimeters of ATLAS and CMS have been optimized to have the best possible jet energy resolution and missing transverse energy (E_T^{miss}) resolution compatible with the space constraint of the experiment.

2. Requirements on the calorimeters at the LHC

The typical energy of the photons in the $H \rightarrow \gamma\gamma$ channel is around 50 GeV. A di-photon invariant mass resolution of 1% is required to disentangle the H mass peak from the background. The detector must be granular to allow a good $\pi^0 \rightarrow \gamma\gamma$ separation and reduce the QCD background. The $H \rightarrow 4$ electrons channel requires full coverage in ϕ and $|\eta|$ up to 3. The range of the calorimeter must be able to reach about 2 TeV to cope with high mass resonances (like the Z').

The energy resolution of a calorimeter can be parametrized as:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c. \quad (1)$$

The term a takes into account the stochastic fluctuations, it is small for homogeneous calorimeters and higher for sampling calorimeters. This term limits the low energy performance. The b term is due to electronics noise and the constant term c takes into account the detector disuniformities or instabilities and the error on the calibration and it limits the high energy performance. The experiments have put a lot of effort to contain its effect.

The hadronic calorimeters must contain jets up to 1 TeV, so approximately 11 interaction lengths (λ_I) are required. They have to be hermetic not to spoil the E_T^{miss} resolution, so a coverage up to $|\eta| \leq 5$ is required. They have to tag forward jets and measure their energy with satisfactory resolution for the E_T^{miss} computation. Thus both experiments have installed a forward calorimeter to extend the η coverage from 3 to 5.

The detectors must be compact, fast, radiation hard and reliable for at least 10 years.

3. The ATLAS experiment

The ATLAS experiment is the largest of the LHC experiments, it is 40 m long and 22 m tall. It is made of a large muon spectrometer with three air-core toroidal magnets, a silicon tracker with transition radiation straw tubes for particle identification inserted in a 2 T super-conductive solenoid field, a highly segmented liquid argon electromagnetic calorimeter and a tile calorimeter to measure jets. The solenoid coil is in the cryostat just in front of the electromagnetic calorimeter.

4. The Compact Muon Solenoid experiment (CMS)

The CMS experiment is made of a super-conducting solenoid, providing a 4 T magnetic field, which contains the silicon tracker and the calorimeters. Muon chambers are embedded in the iron return yoke. A crystal electromagnetic calorimeter and a sampling brass and plastic scintillator hadronic calorimeter are located inside the coil.

5. Electromagnetic calorimeters

5.1. *The ATLAS electro-magnetic calorimeter*

The ATLAS sampling electromagnetic calorimeter is made of liquid argon (LAr) and lead absorber plates shaped as an accordion and operated in a cryostat at 87 K. The signal is given by the ionization electrons collection, it is linear and uniform, stable in time and intrinsically radiation hard. The modules are longitudinally segmented: the front sampling is made of narrow strips for better separation of the π^0 photons, the middle sampling (16-18 X_0) collects most of the shower energy, the back sampling (2 X_0) catches the tail of high energy showers and helps to separate hadrons from electrons. A thin presampler is installed for $|\eta| < 1.8$. The calorimeter depth is $25X_0$ and the number of channels is about 170000.

Keeping the mechanical tolerance in the absorber thickness at 2 mm within $9\mu\text{m}$ was a challenge. The obtained precision guarantees uniform cell response and contributes to the constant term c for less than 0.2%.

The energy resolution of the LAr calorimeter measured in test-beams (see Figure 1) is $\sigma(E)/E = 10\%\sqrt{E} \oplus 0.17\%$. Long range non uniformities contribute to c for 0.44% giving a global constant term around 0.7%. The measured linearity is better than $\pm 0.1\%$ for electron energies between 10 and 180 GeV. In total 10% of the calorimeter modules have been exposed to test-beams.

The electronics calibration is sufficient to inter-calibrate the channels thanks to the high mechanical uniformity. Simulation shows that with 50000 $Z \rightarrow ee$ events (achievable in 0.1 fb^{-1}) the constant term can be contained to 0.7%.

5.2. *The CMS electro-magnetic calorimeter*

The CMS electro-magnetic calorimeter (ECAL) is a homogeneous calorimeter made of 75000 lead tungstate (PbWO_4 or simply PWO) crystals ($X_0=0.89 \text{ cm}$). The crystals, developed after a long R&D phase, are 23 cm long, corresponding to $25 X_0$. The light is fast but the light yield is small ($LY \simeq 100 \gamma/\text{MeV}$). The light is measured via avalanche photodiodes (APD) in the barrel and vacuum phototriodes (VPT) in the endcaps, due to the higher level of radiation. Being a homogeneous calorimeter, the stochastic term is small, so the performance at high energy is limited by the constant term c .

Very stable cooling and high voltage systems guarantee a small contribution to c (0.1-0.2%). Due to the intrinsic fluctuations of the shower maximum depth, a potentially dangerous contribution to c could be the disuniformity of the light collection along the crystals. This has been contained to 0.3% by depolishing one of the crystal lateral faces. The radiation level in the detector causes transparency loss, thus reducing the signal level. A light injection system monitors transparency changes, keeping the effect on c below 0.2%.

Several ECAL modules have been tested with high energy electron beams. The energy resolution (see Figure 1) is $\sigma(E)/E = 2.8\% \sqrt{E} \oplus 125 \text{ MeV}/E \oplus 0.3\%$.

All the barrel modules have been inter-calibrated with 1-2% precision with cosmic rays and 25% of them have been calibrated to 0.4% with high energy electrons beams. At the LHC the calibration will be performed using physics events. The crystals with precise calibration will help understanding the calibration with physics events and especially the effect of the material in front.

5.3. *Detector performance and status*

The tracker material in front of the ECAL reaches about one X_0 . In ATLAS the solenoid coil adds 2-4 X_0 just in front of the ECAL that may cause energy loss and contribute to the stochastic term. High energy electrons traversing the tracker material emit Bremsstrahlung that

generates separated cluster in the ECAL due to the magnetic field. So smart reconstruction algorithms are used to recover radiated energy. Photon reconstruction is also affected due to photon conversion that generates fake tracks, thus reducing the photon efficiency.

Full simulation studies of the $H \rightarrow \gamma\gamma$ channel show that the H mass resolution is as expected and it will allow a discovery in about 10 pb^{-1} . Nevertheless this analysis requires a well calibrated and understood ECAL and a well aligned tracker to find the event vertex. So the commissioning phase and the ability to reach fast a good calibration level will be crucial.

Both calorimeters are built and installed. The CMS Endcaps are being assembled and will be finished by June 2008.

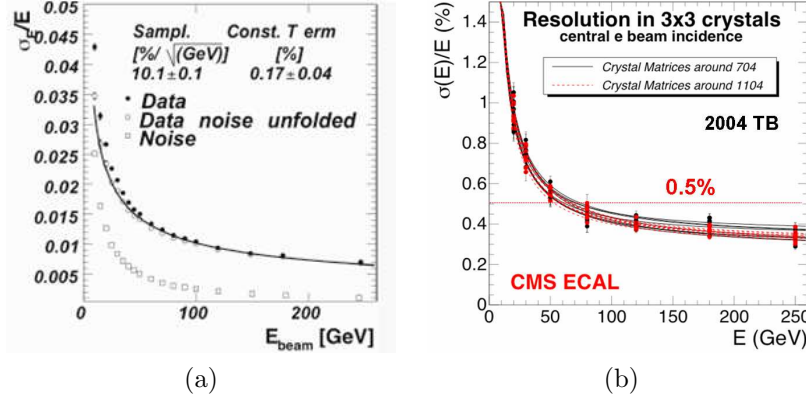


Fig. 1. The ATLAS (a) and CMS (b) ECAL energy resolution.

6. The hadronic calorimeters

6.1. The ATLAS hadronic calorimeter

The ATLAS hadronic calorimeter (HCAL) is made of a Barrel and two endcap modules. The endcaps, closed in the same cryostat as the endcap electromagnetic calorimeter, are made of copper plates and use LAr as an active medium. The Barrel HCAL is made of steel and plastic scintillator tiles arranged parallel to the beam line. The scintillation light is collected by wavelength shifting fibers (WLS) and read by PMTs at the back. The barrel covers up to $|\eta| = 1.7$ and two extended sections with the same technology surround the copper/LAr endcap calorimeter. The ATLAS HCAL is non

compensating ($e/h \simeq 1.4$). It reaches 9.7 to 13 λ_I and the energy resolution in the barrel for pions is $\sigma(E)/E = 45\%/\sqrt{E} \oplus 1.3\%$.

6.2. *The CMS hadronic calorimeter*

The CMS hadronic calorimeter (HCAL) is made of brass and plastic scintillator tiles arranged transversal to the beam line. WLS fibers are used to collect the light and clear optical fibers carry the light to hybrid photodiodes at the back. The design energy resolution for pions is: $\sigma(E)/E = 100\%/\sqrt{E} \oplus 8\%$.

The HCAL is 7 λ_I deep at $\eta = 0$. Another HCAL layer has been installed outside the solenoid to add 3 λ_I . This improves by 10% the energy resolution for 300 GeV pions and improves the linearity. The HCAL is non compensating ($e/h \simeq 1.4$). The use of energy dependent ECAL and HCAL weights allows to improve the energy resolution and the linearity but the non compensation and the poor containment limit the performance. To improve the jet energy resolution CMS is studying particle flow algorithms, which measure charged particles in the tracker, photons in the ECAL and long lived neutral hadrons in the HCAL.

6.3. *Performance, Calibration and commissioning*

Both hadronic calorimeters have been calibrated at 3-5% level with radioactive sources. Many modules have been tested on test-beams also in combination with the ECAL. The detectors are all built, installed and have started taking cosmic rays data in the pit.

Simulation shows that currently the ATLAS E_T^{miss} resolution is better than the CMS one. However recent studies on inclusive supersymmetric searches, where fully hadronic channels are analysed,⁴ show that the ATLAS and CMS potential is similar. Apparently what really counts in this analysis is the hermeticity and the correct Monte Carlo description of the gaps in the detector rather than the resolution.

7. The LHCb experiment

The LHCb experiment⁵ uses B-hadrons produced with high rate at small angle to study CP-symmetry violation in the neutral B meson system. It is a single arm spectrometer that covers the angle from the beam between 10 and 300 mrad. The detectors are assembled in two halves. The calorimeters must give electron/hadron separation, electron energy and position measurement for the first trigger level and for offline analysis.

The ECAL is a Pb/scintillator/WLS Shashlik calorimeter. The total length is $25 X_0$. Just in front of the ECAL a scintillator pad detector and a pre-shower help the electron/hadron separation. The granularity decreases with radial distance from the beam. Test-beam results show that the energy resolution is $\sigma(E)/E = 10\%/\sqrt{E} \oplus 1\%$, which is sufficient for hadron rejection and for π^0 reconstruction. A monitoring system with LED is used to compensate for radiation damage. The initial calibration will be obtained using cosmic rays and then using energy flow and $\pi^0 \rightarrow \gamma\gamma$ decay.

The HCAL is made of iron and scintillator tiles mounted parallel to the beam line. It constitutes $5.6\lambda_I$ and has a resolution of $a = 80\%/\sqrt{E} \oplus 10\%$.

The calorimeters are installed in the pit and the commissioning phase has started.

8. The Alice experiment

The Alice experiment⁶ will study heavy ion collisions at the LHC, to investigate the quark-gluon plasma formation.

Alice has a photon spectrometer (PHOS) to study direct single photon and di-photon production in the collision initial phase and jet quenching via high p_T photons and π^0 . Typical photon energies are between 0.5 and 10 GeV. It is made of 17000 PWO crystals read by APDs and operated at -25°C to optimize the response for low energy showers. Its depth is $20 X_0$. It is at 4 metres from the interaction point and it covers $|\eta| < 0.12$ and 100° in ϕ . Its performance measured in test-beams is: $\sigma(E)/E = 3.3\%/\sqrt{E} \oplus 18 \text{ MeV}/E \oplus 1.1\%$. The first of the five modules is ready and installed.

9. Conclusions

It was a challenging adventure to build calorimeters with this number of channels and the required level of reliability for ten years or more in the LHC environment. The detector performance was extensively tested in test-beams and meets the design specifications. Most of the detectors are built and the commissioning phase has started. Preliminary simulation studies show that the obtained calorimeters performance allows to reach the desired physics goals. We are looking forward to seeing interesting physics with them.

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